

The Brightest of Reionizing Galaxies (BoRG) survey

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Abstract.

Until now, investigating the early stages of galaxy formation has been primarily the realm of theoretical modeling and computer simulations, which require many physical ingredients and are challenging to test observationally. However, the latest Hubble Space Telescope observations in the near infrared are shedding new light on the properties of galaxies within the first billion years after the Big Bang, including our recent discovery of the most distant proto-cluster of galaxies at redshift $z \sim 8$. Here, I compare predictions from models of primordial and metal-enriched star formation during the dark ages with the latest Hubble observations of galaxies during the epoch of reionization. I focus in particular on the luminosity function and on galaxy clustering as measured from our Hubble Space Telescope Brightest of Reionizing Galaxies (BoRG) survey. BoRG has the largest area coverage to find luminous and rare $z \sim 8$ sources that are among the first galaxies to have formed in the Universe.

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INTRODUCTION

The first billion years after the Big Bang represent a key area of astrophysics, with interesting problems, open questions and potential for unexpected and unusual discoveries as highlighted by the 2010 Astronomy Decadal Survey Report¹. Significant progress has been made in the field in the last few years. Numerical simulations are following formation of the first stars at progressively high resolution (see reviews by Yoshida and Abel in this volume) and simulations of first galaxies from first principles are now growing in dynamic range [1, 2]. Theoretical models can be constructed to investigate and predict the star formation rate during and after the epoch of Reionization at $z \gtrsim 4$ [3, 4] (see Fig. 1).

Observationally, the quest for direct detection of first stars seems very difficult, with these sources being too faint (a $100 M_{\odot}$ Pop III star at $z > 6$ has observed magnitude $M_{AB} \gtrsim 38$). However, prospects of indirect detection of metal-free stars are intriguing, either through high- z supernovae, or if gravitational lensed and living in small clusters [5, 6]. In terms of observations of high-redshift galaxies, recent progress has been done thanks to the installation of Hubble's WFC3, leading to the identification of large samples of galaxies at $z \sim 7 - 10$ (see review by Bouwens in this volume).

¹ http://www.nap.edu/catalog.php?record_id=12951

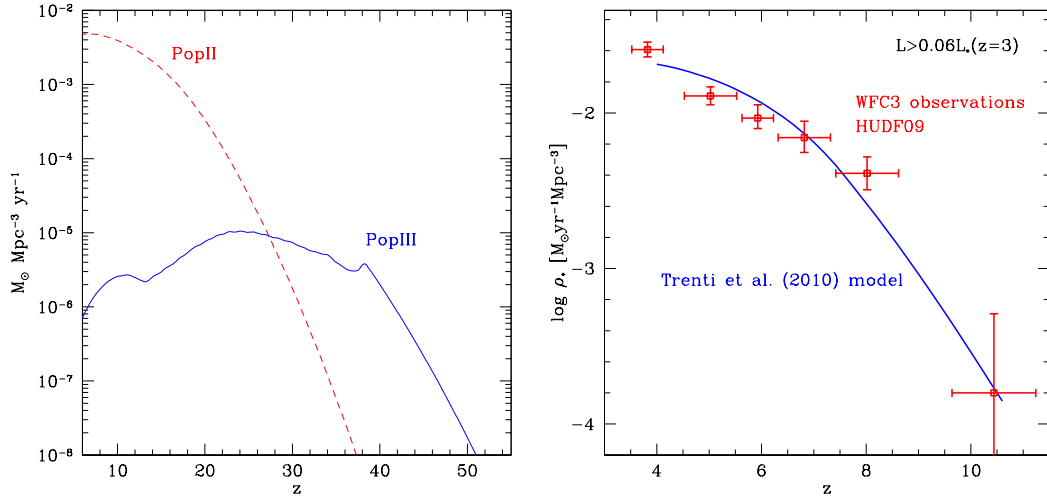


FIGURE 1. Left panel: Pop III (blue solid line) and Pop II (red dashed line) star formation rates based on an analytical model including chemical enrichment and radiative feedback (adapted from [3]). Radiative feedback in the LW bands keeps the Pop III star formation rate approximately self-regulated from $z \sim 35$ to $z \sim 20$. Right panel: Evolution of SFR density at high redshift, adapted from WFC3 data of [7], with luminosity density converted to $\dot{\rho}_*$ (see their Table 3). The solid blue curve shows the predicted evolution from a conditional luminosity function model [4] based on the evolution of the underlying dark-matter halo mass function. The model is successful in reproducing the observed $\dot{\rho}_*$ and captures the rapid drop from $z \sim 8$ to $z \sim 10$.

In this contribution, I briefly summarize some of my recent results on star and galaxy formation at high redshift, starting from a short discussion of metal-free versus metal enriched star formation during the epoch of reionization (and spatial inhomogeneities in chemical enrichment), and then focusing on observations of the most overdense regions in the universe at $z \sim 8$ through the Brightest of Reionizing Galaxies survey.

STAR FORMATION DURING AND AFTER THE DARK AGES

The first stages of star formation at $z \gtrsim 20$ have very well defined initial conditions, so simple analytical modeling can make clear predictions of the relative interplay between metal-free and metal-enriched star formation. With a model for molecular hydrogen cooling, radiative feedback in the Lyman Werner (LW) bands, plus chemical enrichment (from metal free to above critical metallicity of $Z \sim 10^{-3.5} Z_{\odot}$), we have predicted the formation rate of Pop III (metal-free) and Pop II (metal-enriched) stars at very high redshift [3]. Star formation begins very early in the Universe (at $z \gtrsim 60$, see also [8]) and the Population III star formation rate rises exponentially with redshift until sufficient radiative feedback in the LW bands sets in, at $z \sim 35$ (Fig. 1). Assuming massive Pop III stars, chemical enrichment of the interstellar medium leads to Pop II star formation to become the dominant already at $z \sim 25$. Yet, because of the non-linear relation between redshift and star formation, most Pop III stars are produced at $z \lesssim 20$.

At lower redshift ($z \lesssim 10$), a simple analytical model for chemical enrichment is

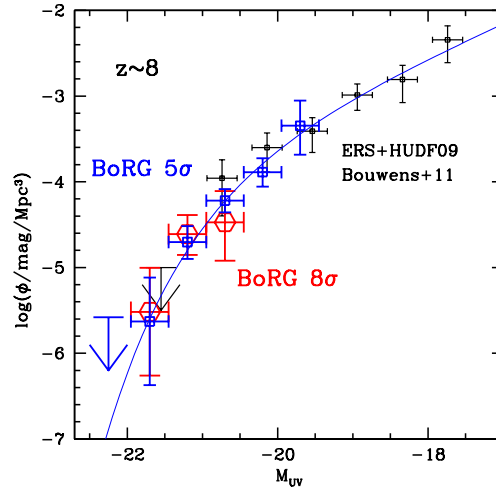


FIGURE 2. Luminosity Function at $z \sim 8$ from the BoRG survey for our 5σ and 8σ catalogs (blue and red, respectively), combined with the stepwise LF derived by [12] for the ERS+HUDF09 dataset (black points). The blue line is the best-fit Schechter LF from combining the BoRG+ERS+HUDF09 dataset, providing the widest dynamic range in luminosity that is currently available. Our results are consistent with a Schechter form of the UV LF across all dynamic range probed and the faint-end slope is steep: $\alpha = -1.98 \pm 0.23$.

however no longer able to capture the significant large scale structure that develops in the Universe, with voids of several Mpc^3 (comoving) in volume and the rising importance of metal outflows in winds. Cosmological simulations are required to capture the transition from metal-free to metal-enriched star formation at these later times. This approach shows that Pop III stars continue forming into low-density regions [5, 9], while overdense regions, which had earlier than average Pop III star formation [10], are forming massive galaxies already at $z \sim 10$. These simulated galaxies have stellar masses of about $10^9 M_\odot$, in the range close to those that can be observed at slightly later times with the current generation of Space Telescopes (Hubble and Spitzer, e.g., see [11]).

THE BRIGHTEST OF REIONIZING GALAXIES SURVEY

To investigate galaxy formation during the epoch of reionization in the most massive dark matter halos, expected to host the brightest galaxies such as those simulated in [1], we have launched a large observational campaign with the Hubble Space Telescope (HST) to image random pointings of the sky to $m_{AB} \sim 27$ in the near-IR. The Brightest of Reionizing Galaxies Survey is a four-bands HST survey in the optical (F606W) and near-IR (F098M, F125W, F160W) which identifies $z \sim 8$ galaxies as F098M-dropout (Y-dropout) sources using the Lyman break technique [13].

A full description of the survey and of its results is given in [14, 15, 16]. To summarize the status to date, we observed 59 pointings for a total area of 274 arcmin^2 , which is the largest available to search for $z \sim 8$ galaxies (compared to $\sim 100 \text{ arcmin}^2$ of CANDELS,

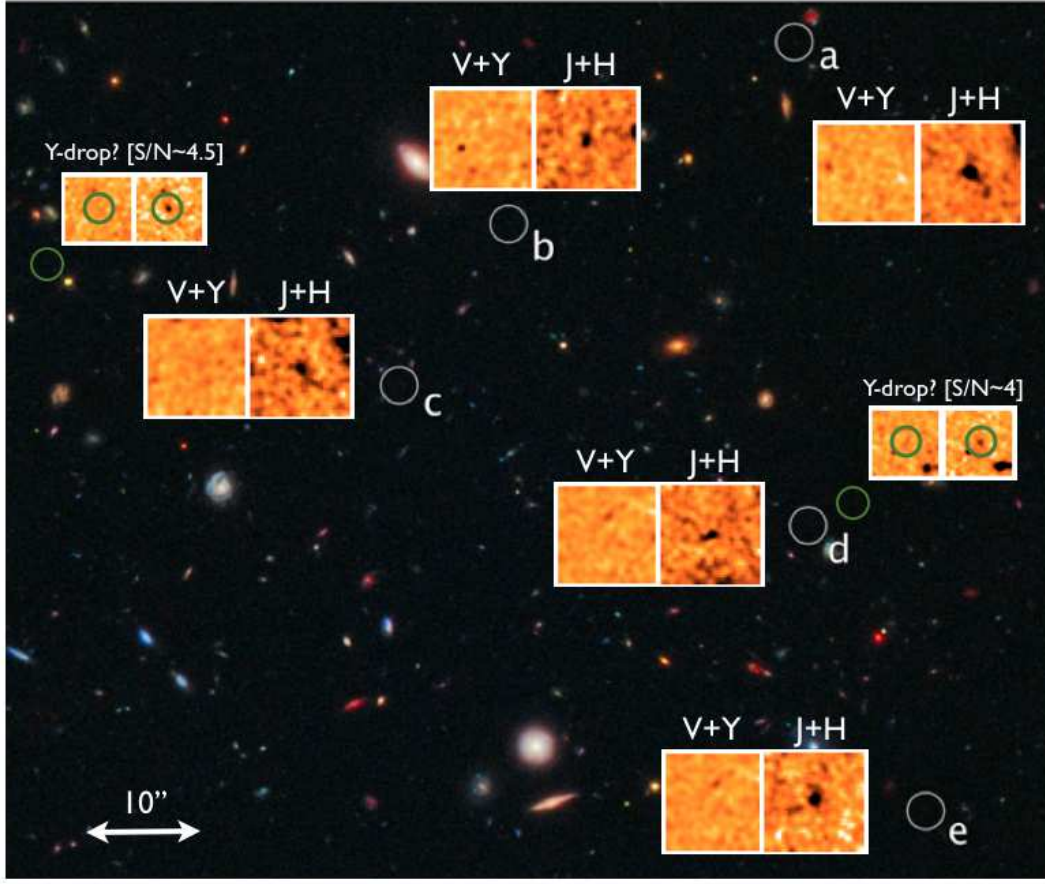


FIGURE 3. VYJH color-composite image of the $z \sim 8$ BoRG58 protocluster region, with postage stamp images ($3''.2 \times 3''.2$) of the five $z \sim 8$ members of the overdensity (sources a-e) discussed in [15]. Also indicated are the locations of two additional Y-dropout candidates that are currently just missing the 5σ detection threshold to be included in our catalog. Upcoming deeper HST observations (GO-12905, PI Trenti) will confirm these additional candidates at $S/N \sim 10$ and are expected to discover additional new fainter members of the overdensity.

see [17]). From this area we identified 33 $z \sim 8$ galaxy candidates at the bright end of the luminosity function. Combining the BoRG data with the ultradeep observations by [12], we constructed a global fit of the galaxy luminosity function at $z \sim 8$ with a Schechter function ($\phi(L) = \frac{\phi_*}{L_*} \left(\frac{L}{L_*}\right)^\alpha \exp(-L/L_*)$), shown in Fig. 2. The best fit has a very steep faint-end slope, $\alpha = -1.98 \pm 0.23$, which suggests that galaxies fainter than the current detection limit of HST at $M_{AB} \sim -18$ contribute significantly to the total ionizing flux emitted at the time (see also the discussion of the same issue in a theoretical context in [4]).

THE MOST DISTANT GALAXY PROTOCLUSTER

The BoRG survey is not only counting galaxies at the bright end of the luminosity function, but it is also identifying special regions in the Universe, “cluster construction zones” that will evolve into the most massive structures today. The brightest $z \sim 8$ BoRG candidates are expected to live in highly biased dark matter halos ($M_{DM} \gtrsim 5 \times 10^{11} M_{\odot}$, bias $b \sim 9$ at $z \sim 8$). As a consequence, they are surrounded by overdensities of fainter galaxies [18, 19]. We verified this prediction at $> 99.9\%$ confidence from BoRG based on field-to-field variations of $z \sim 8$ number counts and identified a protocluster candidate [15]. The best $z \sim 8$ source in the BoRG survey, a $m_{AB} = 25.8 \pm 0.1$ galaxy more than one magnitude brighter than $L_*(z = 8)$ is surrounded by four additional F098M-dropouts in its proximity with $S/N > 5$, within a region of diameter $d \approx 1'$ (or ~ 3 Mpc comoving) that on average is expected to contain only $n \sim 0.2$ such galaxies at $z \sim 8$ (Fig. 3). With $\langle m_{AB} \rangle = 27.1$, the four sources are $L \sim L_*(z = 8)$ galaxies, about ~ 1.3 magnitudes fainter than their bright companion and consistent with being at its redshift. Our detailed statistical analysis, which includes comparison with mock catalogs from cosmological simulations, demonstrates that the overdensity is a physical structure of $\sim 3 - 4$ comoving Mpc in size at 99.97% confidence. Its discovery was expected based on the comoving cosmic volume probed by the survey ($V \sim 5 \times 10^5 \text{ Mpc}^3$). The region started forming the first stars at $z > 30$, assembled a significant fraction of its mass by $z \sim 15$ and will evolve by $z = 0$ into a massive galaxy cluster with $M > 2 \times 10^{14} M_{\odot}$ based on our modeling [15]. Hence, these HST observations are both showing a glimpse of a region that hosted very early star formation, as well as of the infancy of a future massive galaxy cluster.

FUTURE PROSPECTS

BoRG is acquiring new data over the course of 2012 through Cycle 19 observations (HST-GO 12572, PI Trenti). The final area of the survey will grow to about 400 arcmin^2 in the short term, leading to the discovery of more bright $z \sim 8$ candidates, possibly highly clustered as in the case of the protocluster field. Recently approved HST observations of the BoRG protocluster (HST-GO 12905) are expected to lead to the discovery of 6 – 10 new members of the overdensity, confirming theoretical predictions that clustering extends to smaller mass halos containing fainter galaxies [15]. Ground-based spectroscopy (e.g. MOSFIRE at Keck) has the potential to provide the first solid detections of $\text{Ly}\alpha$ emission from sources at $z \sim 8$. Doing so would confirm the redshift of photometric $z \sim 8$ candidates such as those identified by BoRG. More importantly this would also constrain models for the evolution of the neutral hydrogen fraction, which affects the Equivalent Width distribution of $\text{Ly}\alpha$ emission [20]. Finally, Spitzer IRAC observations of luminous galaxies in high- z overdensities have the potential to unveil the properties of stellar populations of some of the first galaxies formed in the Universe, given the biased star formation history of these regions. All this array of future observations, combined with theoretical and numerical modeling, will pave the way to extending the study of galaxy formation to $z \sim 15$ once the *James Webb Space Telescope* will be launched later this Decade.

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